Degenerate gaugino mass region and mono-boson collider signatures

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Abstract

We propose here a program of searches for degenerate electro-weakinos in various final state search topologies. In particular we emphasize the usefulness of searching for mass degenerate charginos and neutralinos in the mono-Z search channel. We demonstrate that the mono-Z search supercedes the mono-jet and mono-photon search topologies and present arguments using effective operators to explain why mono Z searches can succeed where mono-jet and mono-photon searches have failed.

1 Introduction

Electroweakinos, in most of supersymmetric model-space are the most likely candidates for the SUSY spectrum's Lightest Supersymmetric Particle (LSP) or Next-to Lightest Supersymmetric Particle (NLSP). Moreover in many appealing models, the lightest chargino and neutralino, either Wino of Higgsino-like are quite mass degenerate. Example included minimal versions of anomaly mediation, mirage mediation [1–3], or Higgsino-world scenarios.As the first kinematically accessible states, it is important to create SUSY searches which will be sensitive to these particles. However in the mass degenerate scenario searches for electroweakinos (ewkinos) become quite hard, involving such non-standard topologies as displaced vertices, as kinks disappearing tracks.

While supersymmetry (SUSY) remains the leading candidate for weak physics beyond the Standard Model, current searches at LHC have not yet revealed supersymmetric particles. Minimal version of leading Supersymmetric communication schemes, mSUGRA, gauge mediation and anomaly mediation predict relatively similar particle spectra with the heaviest sparticles being squarks, roughly an order of magnitude heavier than the lightest supersymmetric particles the electro-weak gauginos. In such models the hope was that the smoking gun signal for supersymmetry would be in a jets plus missing energy channel from the strong production of pairs of gluinos or squarks. In view of models with maximal naturalness, these particles were hoped to be under 1 TeV in mass. Current constraints, however, are pushing us to look for SUSY in different places. Current bounds from ATLAS and CMS have pushed mass bounds for squarks and gluinos which decay into typical jets plus missing energy channels, into the 1-2 TeV range. Separately, the Higgs mass constraint of 126 GeV hints that squark masses should reside in the multi-TeV range in order to facilitate large loop contributions to the tree level Higgs mass. Much reasonable model space exists where squarks may be in the 10 TeV range. Indeed the LHC 5-sigma discovery potential for gluinos is less than 2 TeV. In light of the possibility of spectra with heavy colored sparticles, one must reconsider the channels in which supersymmetry is most likely to make its first appearance, and electroweak-inos become an important discovery channel for SUSY.

We propose here a program of searches for degenerate electro-weakinos in various final state search topologies. In particular we emphasize the usefulness of searching for mass degenerate charginos and neutralinos in the mono-Z search channel. We argue that this channel may supersede searches with more non-standard topology. We also make arguments as to why mono Z searches can succeed where mono-jet and mono-photon searches have failed.

2 The electroweakino spectrum

The masses of the ewkino sector are fixed by the Majorana mass parameters of the pure bino and wino M_1 and M_2, and also by the mu term, and tanβ. In minimal scenarios such as mSUGRA, or minimal gauge mediation, and simple versions of anomaly mediation M_1 and M_2 do not vary independently. Most generally however the ratio between M_1 and M_2 can vary. There is a wide region of MSSM parameter space exists with mass degenerate chargino and neutralino, all that is needed is that the lightest chargino is Wino or Higgsino like. Here we consider three benchmark scenarios:

- $M_2 << \mu \simeq M_1$ In the limit, the LSP and the NLSP is a pure wino.
- $M_2 \simeq \mu << M_1$ In the limit, the LSP and the NLSP are a wino-Higgsino mixture.
- $\mu << M_2 \simeq M_1$ In this limit, the LSP and the NLSP are a pure Higgsino.

The mass difference between the LSP and the NLSP at tree level is set by the three parameters above and $\tan\beta$ [4]:

$$\Delta M = m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} = \frac{M_W^2}{\mu^2}\frac{M_W^2}{M_1 - M_2}\tan^2\theta_W \sin^2 2\beta + \mathcal{O}\left(\frac{1}{\mu^3}\right) \tag{1}$$

In addition, there are 1-loop electroweak corrections to the chargino masses that make the charginos heavier by about 150 MeV. The mass splitting of the lightest chargino and neutralino is thus always greater than the pion mass. We will consider benchmark points covering all these three scenarios. The tree-level mass difference is $\tan\beta$ suppressed. So at large $\tan\beta$, the splitting is smaller. We will fix $\tan\beta = 30$ in our benchmark points.

For small mass splitting, the decay of the lightest chargino proceeds through an off-shell W, $\chi^{\pm} \to W^* \chi^0$, dominated by hadrons down to $\Delta m < 10$ GeV and by pions below $\Delta m < 1$ GeV. Further, for mass splittings near the pion mass, the chargino decay width is sufficiently small to produce cm sized displaced vertices [5]. Below we compile a series of benchmark points for Wino-like, Higgsino-like and well-mixed chargino scenarios to demonstrate mass splittings and chargino lifetimes.

The possibilities for chargino decay topology are numerous and highly dependent on the chargino-neutralino mass splittings. For mass splittings between 10s and 1 GeV, the decay of the chargino is prompt, and the decay signature is missing energy plus soft jets. For $\Delta m < 1$ GeV the decay is not prompt, and the chargino will travel μmeters or more. In Fig. 1, we have constructed a diagramatic picture of these possible decays which are elaborated on below. If the chargino penetrates several layers of the TRT it may leave a detectable track,

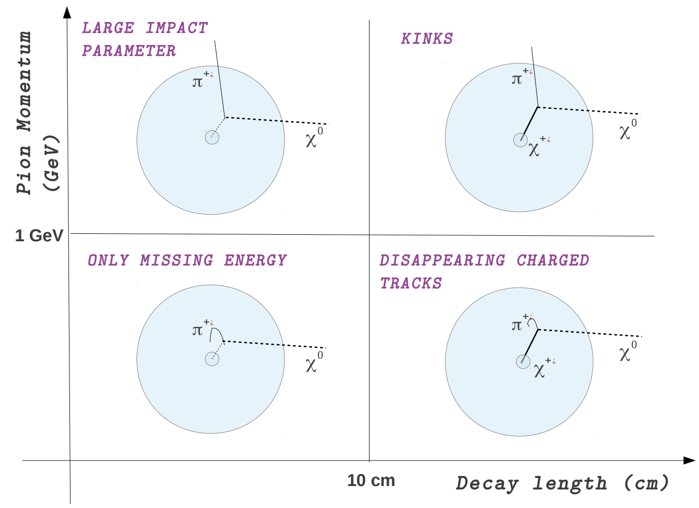

Figure 1: Possible chargino decay topologies with macroscopic chargino lifetime

then depending on the decay products momentum the event will appear either as a kink, or disappearing track. If the chargino is lifetime is macroscopic, yet not large enough to penetrate sufficiently into the TRT before it decays, the decay will appear either as a track with a large impact parameter, or pure missing energy again depending on the momentum of the decay products.

Point	μ	M_2	M_1	$m_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_1^0}$	ΔM	$\tau_{\tilde{\chi}^\pm}$
Wino 1(98% Wino)	700	100	200	98.07	98.06	0.152	92.8216
Higgsino 1(98% Higgsino)	600	300	3000	292.27	292.26	0.178	39.1402
Wino 2 (96% Wino)	540	150	180	145.71	145.54	0.321	4.3766
Mixed 1(72% Wino and 23 % Bino)	500	200	200	193.22	191.25	2.12	0.00241474
Higgsino 2	150	300	1200	136.38	130.26	6.29	1.98665×10^{-5}
Mixed 2(65% Wino and 23 % Bino)	360	200	200	186.13	182.21	4.07	7.06516×10^{-5}
Mixed 3(28% Wino and 23 % Bino)	180	200	200	138.27	127.75	10.68	5.30822×10^{-7}

Table 1: We compile a series of benchmark points for Wino-like, Higgsino-like and well-mixed chargino scenarios to demonstrate mass splittings and chargino lifetimes.

3 Testing Topologies : Mono Boson

In the pair production of ewkinos $pp \to \chi^0\chi^0, \chi^+\chi^0, \chi^+\chi^-$, the decays will be pure $E_{\mathrm{T}}^{\mathrm{miss}}$, $W^* + E_{\mathrm{T}}^{\mathrm{miss}}$, and $W^*W^* + E_{\mathrm{T}}^{\mathrm{miss}}$ respectively. The decay products of charginos in this case are extremely soft. In this case both charginos and neutralinos appear to simple searches purely as missing energy. One may hope to discover the pair produced ewkinos by triggering on a particle emitted as initial state or final state radiation. We note that for $\Delta m <\sim 10$ GeV, the mono-boson plus + $E_{\mathrm{T}}^{\mathrm{miss}}$ channels will be viable search topologies. For $\Delta m <$ 1GeV, options such as disappearing tracks also become viable search channels since these topologies also rely on hard ISR particles to trigger on.

We will below consider three possible mono-boson event topologies, $pp \to$ jet + $E_{\mathrm{T}}^{\mathrm{miss}}$, $pp \to \gamma + E_{\mathrm{T}}^{\mathrm{miss}}$, $pp \to Z + E_{\mathrm{T}}^{\mathrm{miss}}$, or events with a mono-jet, mono-photon, and mono-Z. Since the charginos also appear to these searches as missing energy, we must consider to total production cross section of a mono-boson plus all pairs of ewkinos. We show in Fig. 2, the mass dependence of the total production cross section for Wino-like, Higgsino-like, and mixed gaugino pairs for the mono-jet, mono-photon, and mono-X final states.

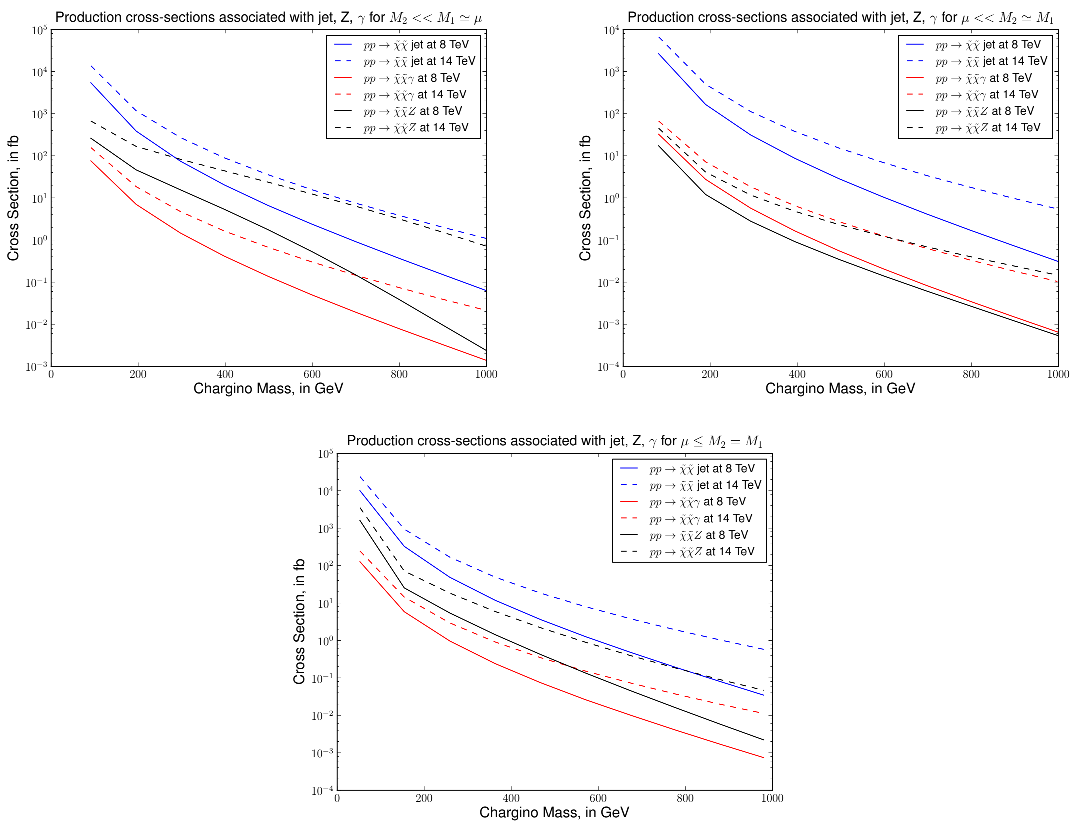

Figure 2: Total ewkino production cross-sections for mono-jet mono-photon, and mono-Z topologies

We will now explore the effectiveness of searches in the mono-photon, mono-jet, and mono-Z final states. In this work we have both attempted to recast existing CMS and ATLAS searches from the first run of LHC and to present a sensitivity analysis for the 14 TeV run. We note that in [6] the criteria for the signal to be observable is that:

$$S \geq \max \left[5\sqrt{B}, 5, 0.2B \right] \tag{2}$$

where S and B are the expected signal and background events.

3.1 Mono-jets

We have implemented the CMS search for monojets in 19.5 fb^{-1} of data [7]. The search had the following cuts triggers and cuts:

- $\not{E}_T > 120$ GeV.
- Jet $p_T > 80$ GeV. $|\eta| < 2.6$.
- Analysis is performed in 7 signal regions binned by $\not{E}_T$ and the highest jet is required to have $p_T > 110$ GeV and $|\eta| < 2.4$.
- Events with 3 jets with higher than 30 GeV p_T and $|\eta| < 4.5$ are rejected. A second jet is allowed if $\Delta\phi(j_1, j_2) < 2.5$.
- Events with an isolated electron or muon with $p_T > 10$ GeV or tau with $p_T > 20$ GeV are rejected.

Backgrounds for this process inculded W/Z + jets, $t\bar{t}$, single t, and QCD multijets. CMS found no excess in mono-jet events over standard model background. CMS placed an upper on number of mono-jet events at 4695 with a jet $p_T > 250$ GeV.

In order to recast this search events for ewkino pair production were simulated using `MadGraph5 v12` [8], showered events with `Pythia8.175` [9], and ran events through the `PGS` detector simulator. Cuts were implemented on the simulated data. Below we show for a benchmark point of mass 113 GeV the total production of $\chi\chi + j$ and the effect of each cut on the total number of passing events.

Cross section for 113 GeV chargino (pair + associated) production	3971 fb
Number of chargino events expected at 20 fb^{-1}	77434
Jet $p_T > 80$ GeV, $|\eta| < 2.6$.	69270
Veto events with 3 jets with higher than 30 GeV p_T and $|\eta| < 4.5$	63920
Events with second jet is allowed if $\Delta\phi(j_1, j_2) < 2.5$	39880
Missing Energy Trigger $E_T > 120$ GeV	5526
Isolated Lepton Veto	5526
Signal Region 1 $\not{E}_T > 250$ GeV	739
CMS Observed Upper Limit for Signal Region 1	4692

Table 2: Cutflow for the monojet analysis for a chargino of mass 113 GeV

We note that for this benchmark point we fail to reach the CMS search sensitivity by a factor of 5. We note two problems with the mono-jet analysis. One is simply the overall magnitude of the expected backgrounds compared to the signal, but the other is the overall softness of the leading jet in signal events. We plot in figure 4 the total number of events binned by jet p_T of the mono-jet signal and the expected SM backgrounds (here we have scaled the signal production cross-section to make it visible under the background). Note that both the signal and the background peak at low jet p_T. Thus large cuts demanded on jet p_T to suppress background also kill the signal.

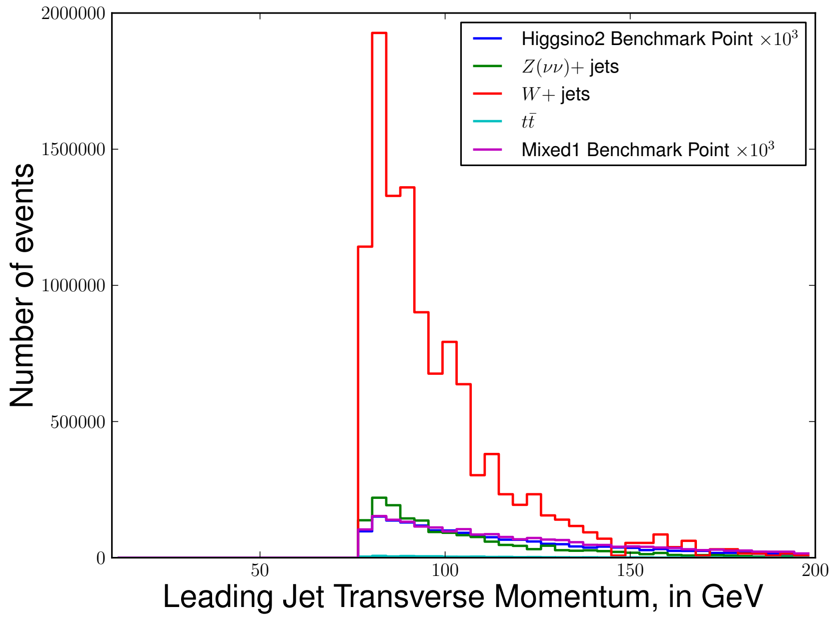

Figure 3: Leading jet p_T vs Number of events expected at 8 TeV. The signal distribution peaks at 50 GeV. Note that in this plot, we have already vetoed events with great than 3 hard jets. We will keep only events which have a leading jet of $p_T > 80GeV$. Note in order to make the signal visible it has been scaled by a factor of 1000.

For our 8 TeV we find that due to the shape of the softly emitted ISR, we fail to meet sensitivity for our mixed scenario benchmark point. This finding is in general in keeping with the statements in [?] for the Higgsino LSP scenario in which $S/\sqrt{B}$ was generally only a few percent.

3.2 Mono-Photon

In an attempt to find a lower-background search, we implemented the mono-photon at 4.6 fb^{-1} by the ATLAS collaboration [10].
The searches cuts were as follows:

- Trigger: Missing Transverse momentum greater than 70 GeV
- Missing energy $\not{E}_T > 150$ GeV calculated with all particles with $|\eta| < 4.9$
- Photon with $p_T > 150$ GeV and $|\eta| < 2.37$ and excluding the barrel/end-cap region $1.37 < |\eta| < 1.52$.
- Photon must be isolated: Energy in a cone of radius $\Delta R = 0.4$ around the photon is required to be less than 5 GeV.

- Events with more than one jet with $p_T > 30$ GeV and $|\eta| < 4.5$ are rejected. Jets are defined by the anti-kT algorithm with a distance parameter of 0.4.
- The photon and the $\not{E}_T$ vector and the jets are required to be well-separated: $\Delta\phi(\gamma, \not{E}_T) > 0.4$, $\Delta R(\gamma, \text{jet}) > 0.4$, $\Delta\phi(\text{jet}, \not{E}_T) > 0.4$.
- Events with electrons of $p_T > 20$ GeV and $|\eta| < 2.47$ and muons of $p_T > 10$ GeV and $|\eta| < 2.4$.

ATLAS found no excess above standard model. We thus may use this search to attempt to constrain ewkino pair production. We recast this search by generating ewkino pair production events using `MadGraph`, showering events with `Pythia`, and using `PGS` for detector simulation.

Below we present, for a 113 GeV chargino mass benchmark point the total ewkino production cross section at 7 TeV, and the effect of each cut in the analysis on the total number of passing events.

Cross section for 113 GeV chargino (pair + associated) + photon production	52.43 fb
Number of chargino events expected at 4.6 fb^{-1}	241.1
Events with more than one jet with $p_T > 30$ GeV and $\|\eta\| < 4.5$ are rejected.	107
Missing energy $\not{E}_T > 150$ GeV	17
Events with leptons are vetoes	17
Photon with $p_T > 150$ GeV	0
CMS Observed Events in Data	116

Table 3: Table from ATLAS Analysis [10].

Again we find that with the high cut on photon p_T needed to suppress the background, the signal is killed. We present in figure 4 a plot of photon p_T vs. number of events in the 7 TeV sample. Note the sharp fall-off in p_T at only 50 GeV.

In the mono-photon case for out mixed LSP we do not expect achieve sensitivity in the 7 TeV sample. Projections for mono-photon prospects at 8 and 14 TeV also failed to reach detectable sensitivity.

4 Effective Operators: Analytic exploration of mono-photon events

We may consider analytically the pair production of neutralinos and charginos along with an ISR or FSR photon. To simplify the calculation, we consider the dimension-7 effective operator coupling gauginos χ to quarks.

$$\mathcal{L}_{B1+B2} = \frac{1}{\Lambda^2}\ \bar{\chi}\chi\ \bar{q}q$$

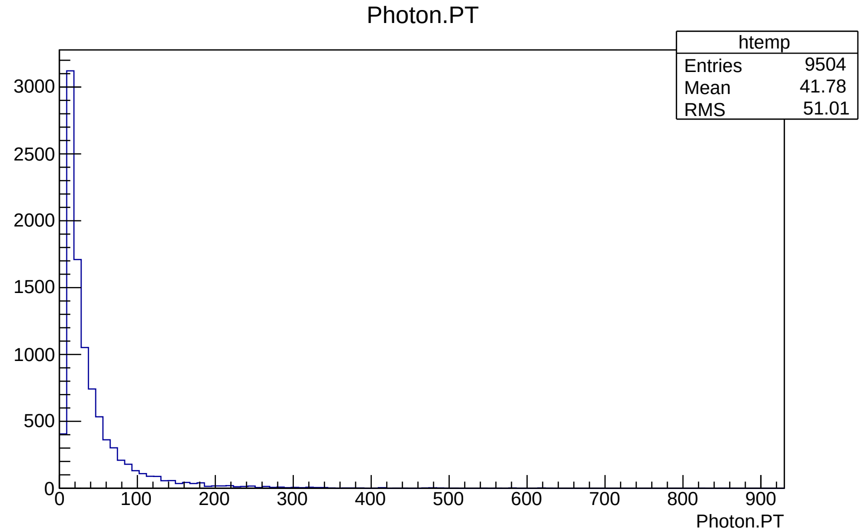

Figure 4: p_T of the photon simulated as seen in the detector simulator.

Using this effective coupling one may now calculate the total production cross section of chargino or neutralino pairs with a photon produced in the initial state. In such a case the analytic form of the Matrix element squared goes like

$$|M|^2 = \frac{32e^2}{\Lambda^4}(p \cdot p^{'} - m_\chi^2)\frac{\sin^2(\theta)}{1-\cos^2(\theta)} \tag{3}$$

Here p and $p^{'}$ are the momenta of the incoming quarks, and θ is the angle between the photon and the beam pipe. The amplitude has a velocity suppression factor due to the mass of the on-shell ewkinos. Most importantly, this matrix element squared has a collinear divergence. That is, the cross section is maximized when the photon radiated in the initial state is in the same direction a the quark aligned with the beam pipe. To determine the dependence of the total production cross section on photon p_T, one must convolve the amplitude with the three body phase space integral. The photon has a minimal energy of 0, and a maximal energy set by phase space of $\sqrt{s} - 2m_\chi$.

When the integral is performed one finds that the cross section would like to grow with photon energy, but at a certain point phase space suppression occurs due to production of on-shell ewkinos kills the production cross section. The photon p_T which defines as

$$pT = E_\gamma \sin(\theta) \tag{4}$$

however, and since the cross section is maximal at low values of θ, the total cross section drops monotonically with increasing p_T.

We can make the following general statement. For events with ISR bosons using the effective operator above, we expect the collinear divergence of the cross section to ensure that the production cross section is dominated by mono-bosons with very low p_T. Such low p_T events will be lost below any but the smallest standard model backgrounds, which are also dominated at low p_T.

5 Mono-Z

As we saw from the previous section we cannot expect that any process dominated by the radiation of one soft jet or photon will be a useful discovery channel for new stable uncharged particles, ewkinos or otherwise. The initial state jet or photon in simple is too soft to be triggered. However if the particle needed to trigger on, which was radiated in the initial state was massive, we might expect to find its decay products. We thus propose mono Z + $E_{\rm T}^{\rm miss}$ as a suitable discovery channel for ewkino pair production. In particular we propose the leptonic final state channel of Z decay as the most promising channel. The relevant event topology is thus, $pp \to Z\chi\chi \to \ell\ell\chi\chi$.

The leptonically decaying Z offers two advantages over mono-jet and mono-photon analyses. One is that the background for the 2 lepton plus $E_{\rm T}^{\rm miss}$ final state is very low. The second is that though we expect the Z to be produced with low p_T, in its decay it will impart the leptons with substantial momentum and provide a possible trigger. We thus implement the ATLAS 7 TeV search in the mono-Z channel. ATLAS performed a search optimized to look for a ZZ final state with one Z decaying to neutrinos, the other to leptons. This search may easily be recast as a search for new physics in the mono-Z final state. The ATLAS search has the following cuts:

- two same-flavor opposite-sign electrons or muons, each with $p_{\rm T}^{\ell} > 20$ GeV, $|\eta^{\ell}| < 2.5$;
- dilepton invariant mass close to the Z boson mass: $m_{\ell\ell} \in [76, 106]$ GeV;
- no particle-level jet with $p_{\rm T}^{j} > 25$ GeV and $|\eta^{j}|$ <4.5;
- $(|p_{\rm T}^{\nu\bar{\nu}} - p_{\rm T}^{Z}|)/p_{\rm T}^{Z} < 0.4$;
- $-p_{\rm T}^{\nu\bar{\nu}} \times \cos(\Delta\phi(p_{\rm T}^{\nu\bar{\nu}}, p_{\rm T}^{Z})) > 75$ GeV.

The Standard Model background to a mono-Z search is mainly the SM production of ZZ where one Z decays invisibly and the other leptonically. In Ref. [11], the ATLAS collaboration measured the ZZ production cross-section at 7 TeV using events that are consistent either with two Z bosons decaying to electrons or muons or with one Z boson decaying to electrons or muons and a second Z boson decaying to neutrinos. The expected backgrounds to the $ZZ \to l^+l^-\nu\bar{\nu}$ channel was reported in Table 6 of Ref. Ref. [11].

We use `MadGraph` version to generate the background events at 7, 8 and 14 TeV, shower them using `Pythia` and perform the detector simulation using `PGS`. For consistency we generated SM background events and found constancy with ATLAS to within a few percent. In Tab. 4 we show the ATLAS SM background processes along with simulated production cross sections for ewkino pairs in three benchmark scenarios of Higgsino-like Wino-like and mixed LSP.

At 7 TeV, with 4.7fb^{-1} of data, we find that it is not possible to see the events from the SUSY scenarios with only about 1 total ewkino pair event expected in the sample. However the situation improves substantially at higher center of mass energy and luminosity. We present below a table with the total number of expected events passing cuts in an 8 TeV sample with 20 fb^{-1} and a 14 Tev Sample with ab^{-1} of luminosity. We note that at 14 TeV we expect that ewkino pair production will be observable at the 2-3 sigma level.

Process	8 TeV LHC	14 TeV LHC
$t\bar{t}, WW, Z \to \tau^+\tau^-$	$19.1 \pm 2.3 \pm 1.0$	14.36
WZ	$20.8 \pm 0.7 \pm 0.5$	17.65
$Z \to e^+e^-, \mu^+\mu^-$	$5.3 \pm 1.1 \pm 1.6$	0
W jets	$1.5 \pm 0.4 \pm 0.4$	0
$W\gamma$	$0.3 \pm 0.1 \pm 0.0$	0
$ZZ \to l^+l^-\nu\bar{\nu}$	39.3 ± 4.0	40.5
Wino 1	5.98	13.663
Higgsino 2	5.04	7.12
Mixed 3	9.15	21.018

Table 4: Number of events from backgrounds and two of the benchmark points for the 8 and 14 TeV LHC. For the 8 TeV LHC, the numbers have been normalized to 20 fb^{-1}.

6 Conclusions

We find that in the SUSY scenario of mass degenerate charginos and neutralinos, the mono-Z search channel is a viable pathway for detection. We have presented general arguments why mono-Z searches may succeed where mono-jet and photon-searches will always give extremely soft radiation on which to trigger.

We note these results are applicable not only to searches for mono-boson plus $E_{\mathrm{T}}^{\mathrm{miss}}$. In particular, in the topologies mentioned where charginos may decay with a displaces vertex, initial state radiation is necessary as a trigger. We note that following our same arguments we expect mono-Z to be a better trigger than mono-photon or mono-jet.

Further, we expect that following our arguments, mono-W events, may also be a possible viable search signature for ewkino pair production.

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